Case 3.1: Turbulent Flow over a 2D Multi-Element Airfoil

Summary of Results

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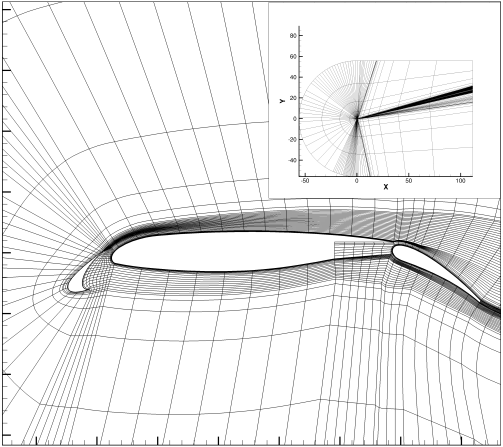
Case description

- **Objective:**
  - Test high-order methods in turbulent flow conditions over a complex geometry.
  - Stiff discrete system poses a challenge for the nonlinear solver.
  - Outputs of interest are lift and drag.
- **Flow and boundary conditions:**
  - $M_\infty = 0.2$ at $\alpha = 16^\circ$.
  - $Re = 9 \times 10^6$ based on $c_{\mathrm{ref}} = 0.5588$, fully turbulent.
  - Adiabatic, no-slip wall at airfoil.
  - Characteristics-based free stream at outer boundary.
- **Gas properties:**
  - $\gamma = 1.4$ and $Pr = 0.71$.
  - Choice of Sutherland's law or constant viscosity.

Geometry and provided mesh

- 4070 (coasest) quartic quads generated via agglomeration.
- Sequence of 3 meshes provided in quad and tri formats.
- Outer boundary located 50 to 100 chord-lengths away from airfoil.
- Inner and outer geometries provided.



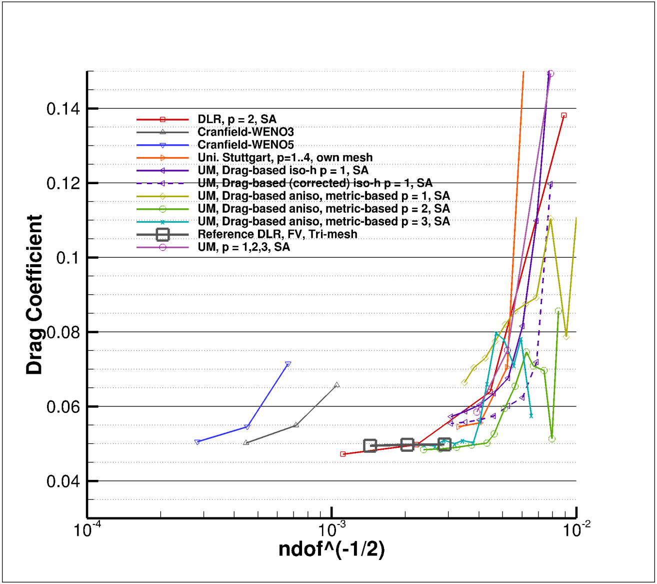
Participants codes and meshes

- **Cranfield:**
  - Spalart-Allmaras (Edwards) turbulence model.
  - WENO, 3rd and 5th-order approximations.
  - Roe or HLLC for inviscid flux, centered average for viscous discretization.
  - Backward-Euler with 1st-order Jacobian, LU-SGS linear solver.
  - Linear triangular meshes with 1000 chord-lengths farfield distance.
  - Convergence study on sequence of non-nested meshes.
  - Runs performed on single-node, two 8-core Westmere cores (16 partitions).
- **Michigan:**
  - Spalart-Allmaras (ICCFD7 version) turbulence model.
  - Metric-based anisotropic, isotropic *h*, and *hp*-adaptation.
  - DG, Lagrange basis, full and tensor-product on reference domain.
  - Roe solver for inviscid flux, BR2 for viscous discretization.
  - CPTC, relaxed line-search, with in-house GMRES and line-Jacobi preconditioner.
  - BAMG mesh (metric-based runs), HOW mesh (quad runs).
  - Runs performed on 6 Westmere cores.

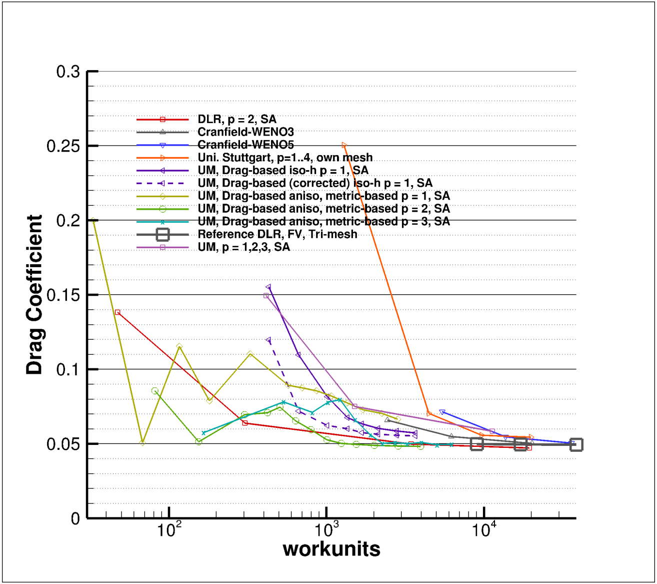
Participants codes and meshes

- **DLR:**
  - Spalart-Allmaras (ICCFD7 version) turbulence model.
  - DG, hierarchical polynomial basis on physical space.
  - Roe solver for inviscid flux, BR2 for viscous discretization.
  - Nonlinear *h*-or-*p*-multigrid with Backward Euler smoother.
  - SER for CFL evolution.
  - Structured curved meshes with farfield at 50 chords.
  - GMRES with *h*-or-*p*-multigrid preconditioner and line-Jacobi smoother.
  - 2, 4, 8, and 16 partitions.
- **Stuttgart:**
  - Spalart-Allmaras turbulence model.
  - DG, modal basis.
  - HLL solver for inviscid flux, BR2 for viscous discretization.
  - PTC solver with ILU-GMRES linear solver.
  - High-order mesh via projection of normals.
  - Runs performed on 8 cores.

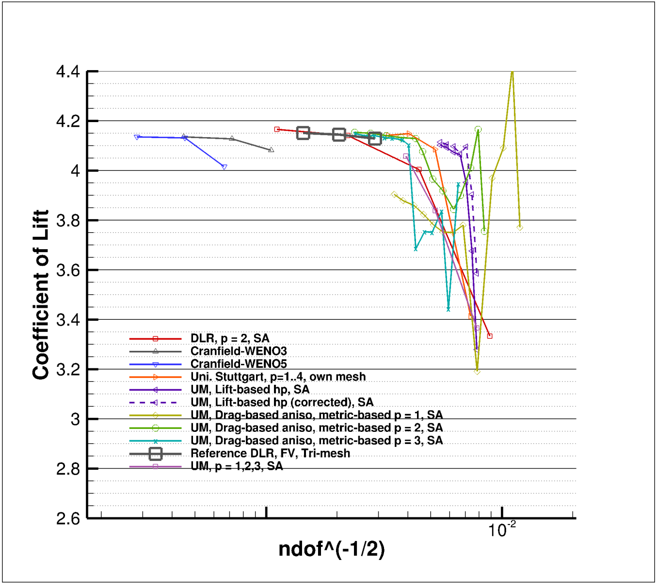
Drag convergence versus DOFs



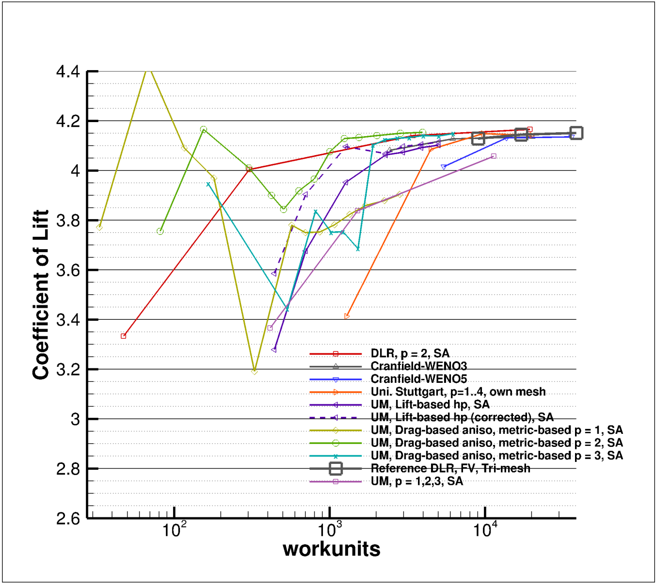
Drag convergence versus workunits



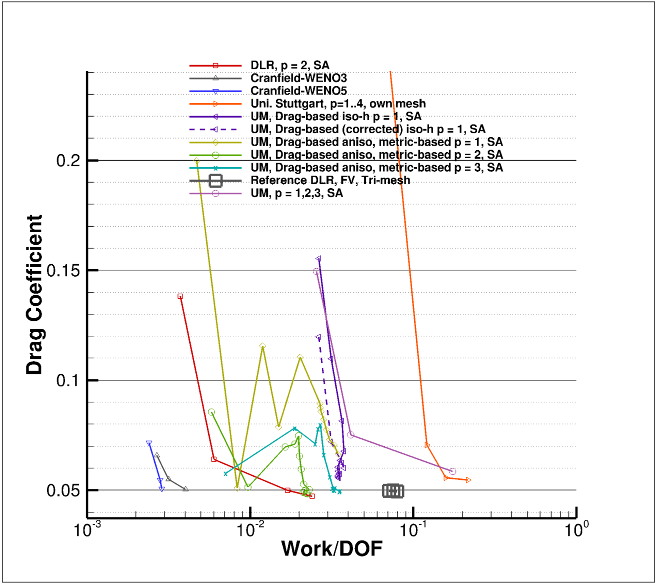
Lift convergence versus DOFs



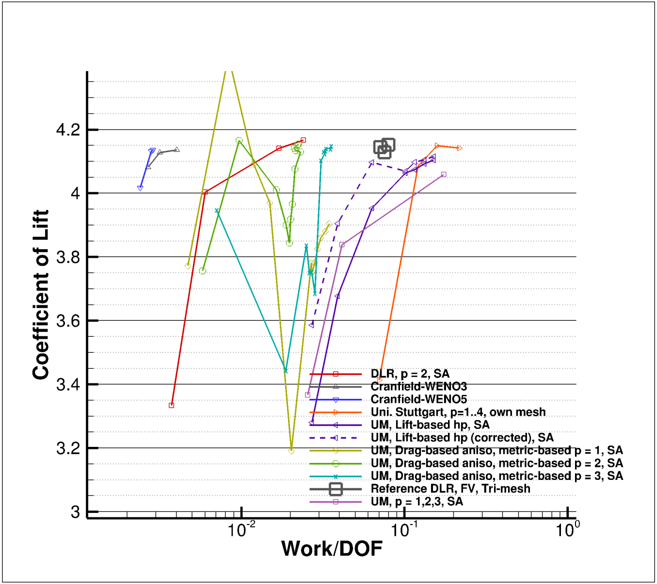
Lift convergence versus workunits



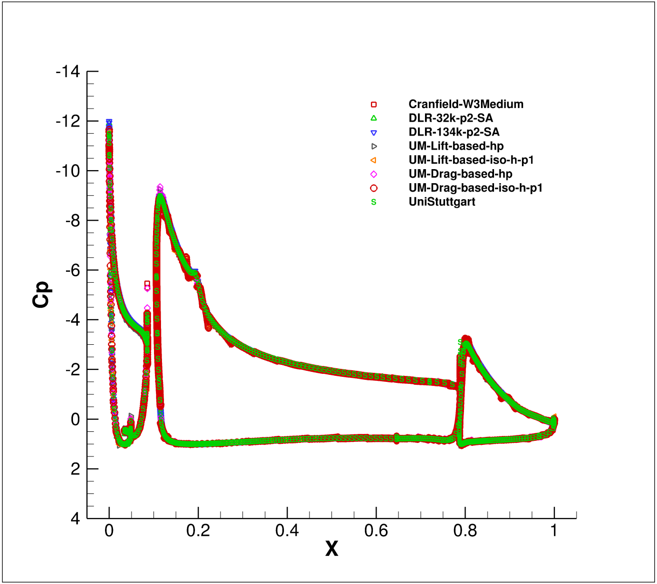
Drag convergence versus Work/DOF



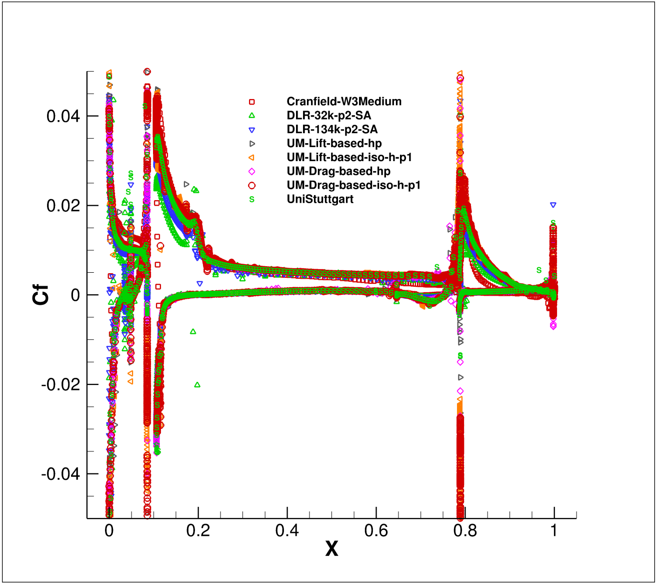
Lift convergence versus Work/DOF



C_p distribution



C_f distribution



Conclusions

- Smaller workunits spread this time.
- Different converged outputs are likely due to different domain boundaries.
- Good agreement between participants for C_p distribution.
- Some variation on C_f.
- Adaptivity saves work, error correction helps but not always reliable specially for lift.
- We would like all to reach constant Work/DOF in our algorithms.